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Scalability of Robotic Controllers: An Evaluation of Controller Options–Experiment III

by Rodger A. Pettitt, Christian B. Carstens, and Elizabeth S. Redden

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14. ABSTRACT
This experiment is the third in a series to investigate scaling robotic controllers for use by dismounted warfighters. A 2 × 2 within-subjects design crossing two controllers (game controller [GC] and virtual joystick [VJ]) with two levels of robotic autonomy (manual control [MC] and click to navigate [CN]) was used. Twenty-two Soldiers conducted reconnaissance tasks on a 200-m course. As a secondary task, Soldiers were told to report course times when prompted. Neither the main effects for controller nor autonomy were statistically significant for driving errors or the number of unexploded ordnance rounds detected, nor were the controller and autonomy interactions. There was a significant controller and autonomy interaction regarding secondary task performance. With the CN feature, there was no significant difference in the efficiency of task performance between the GC and VJ. When using MC, the Soldiers' secondary task performance was significantly more efficient with the VJ than with the GC because the GC required two hands for operation. However, the participants generally preferred the GC over the VJ; the VJ required visual attention because it provided no haptic feedback. They also preferred MC to CN. Suggestions are offered for improving the design of both types of controllers.

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Contents

List of Figures

List of Tables

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1. Introduction

1.1 Background

Robotic interfaces must be tailored to the environment in which they are used and thus, it is important to ensure that interfaces for dismounted warfighters are small and lightweight. A typical load for dismounted warfighters can be well over 100 lb of ammunition and equipment. Injuries frequently occur just from carrying this burden over long distances in rugged and challenging terrain and environments. Dismounted warfighters cannot physically carry the relatively large controllers currently used in stationary environments along with their typical basic loads.

Space to incorporate controls on small-size controllers is very limited. Miniaturizing individual controls as controller sizes get smaller is not always an option as Soldiers wearing gloves have to be able to operate them individually without accidental activation of adjacent controls. Thus the designers of controllers must be creative during functional mapping and this often drives them to the use of multifunction controls. The problems with multifunction controls are that they can increase control activation time and increase the cognitive complexity of the controller. Other creative approaches to controller size reduction that have been developed in the past are sketch interfaces (i.e., using hand drawn sketches to control a team of robots) (Skubic et al., 2003; Setalaphruk et al., 2003), voice recognition and synthesis systems (Chen et al., 2006), and hands-free systems (Veronka and Nestor, 2001), but these novel controls often present problems of their own and they are still being refined.

This experiment is the third in a series of experiments designed to investigate current and future options for scaling robotic controllers specifically for use by dismounted warfighters. In the first experiment, different types of controllers were evaluated with regard to impact on workload, and usability (Pettitt et al., 2008). The controllers used were a multifunction control mounted on a weapon, a game controller with reduced control sizes, and a larger robot legacy controller. Findings indicated that the multifunctional controller was more difficult to learn and use than the controller with the reduced control sizes, most likely due to controller complexity and because switching between functions was time consuming. Also, many tasks often performed simultaneously with the legacy system (i.e., raising the robot arm while driving) could not be accomplished with the multifunctional controller.

In the second experiment, the touch screen interface on an Android phone was compared to a game controller for remotely controlling (teleoperating) robots in an outdoor and an indoor course. Total course completion times, driving errors, and off course errors were significantly better for the game controller than the Android touch screen. The Android touch screen used during that experiment was extremely sensitive, creating many driving errors and requiring the robot to be backed up frequently for repositioning. This added to course completion times. Also, the screen was fairly small and many errors were made because of inadvertent button activation. Recommendations resulting from the experiment included investigation of other touch screens (i.e., those with larger buttons to accommodate human fingers and those with buttons that are placed farther apart than the Android allowed) and use of more autonomous control approaches (Pettitt et al., 2011)

In this experiment we chose two controllers that are commonly used and have the potential to allow a dismounted Soldier to control a small robotic platform and its sensor payload. Because of the difficulty experienced in the second experiment when a relatively small (3.7 in) Android touch screen display was used that combined the display and control functions in one space, we chose a larger (12.1-in) touch screen controller. In addition, this touch screen controller allows supervisory control of the robot, as well as teleoperation. During supervisory control, the robot performs a task autonomously based on an input from the operator, and the operator can resume manual control as needed. Supervisory control reduces the number of fine, sensitive manipulations required to complete a mission, while the larger touchscreen should enable finer and more sensitive manipulations when manual control is required. Because of the promise shown by the gaming controller in the first experiment, we again chose a gaming controller as the baseline for this experiment. Both controllers were programmed to provide the same functions. Pretest experimentation was performed to ensure that the functional mapping of each of the controllers was as effective as possible. In this report we describe and discuss tradeoffs between interface size and weight with these controllers vs. input speed, accuracy, training time, cognitive load, impact on workload, and usability.

1.2 Objective

The goal of this research was to assess the Soldiers' abilities to effectively perform reconnaissance tasks with a robot using a touch screen interface as compared to a commercial off-the-shelf (COTS) gaming controller, each with two levels of autonomy.

1.3 Overview of Experiment

This study was an investigation of the effect of controller scalability on robotic control. It took place at Fort Benning, GA, and 22 Soldiers from the Officer Candidate School (OCS) participated in the study. Two types of control conditions (i.e., a virtual joystick [VJ] touch screen controller and a handheld game controller [GC]) and two levels of autonomy (manual control [MC] with no click to navigate and click to navigate control [CN]) were evaluated. A 2×2 within-subjects design was used, with the four conditions designated as GC/MC, GC/CN, VJ/MC, and VJ/CN. After training on the operation of the robot system, the Soldiers completed an outdoor robotic reconnaissance course, once with each controller type. The sequence of controller type was counterbalanced to control for the effect of learning. Controller type and usability were evaluated based on objective performance data, data collector observations, and Soldier questionnaires.

2. Method

2.1 Participants

Twenty-four Soldiers from the Fort Benning OCS participated in the assessment. Two Soldiers served as participants in pilot testing and twenty-two for the conduct of the experiment. The OCS participants included Soldiers with prior enlisted service who had a variety of backgrounds and experience levels, as well as those just coming into the Army from college.

2.1.1 Pretest Orientation

The Soldiers were given an orientation on the purpose of the study and what their participation would involve. They were briefed on the objectives, procedures, and the robotic system. They were also told how the results would be used and the benefits the military could expect from this investigation. Any questions the subjects had regarding the study were answered.

2.2 Apparatus and Instruments

2.2.1 iRobot 310 Small Unmanned Ground Vehicle[*] (SUGV)

The iRobot 310 SUGV (figure 1) is a tactical mobile robot used to gather situation awareness information, often in areas that are inaccessible or too dangerous for humans. The robot is equipped with an Awarehead[†] payload that has a rotating pan-and-tilt head equipped with multiple cameras. The Awarehead features include:

- Mission tasking control that enables autonomous control.
- Map and video based click-to-drive with obstacle detection and avoidance.
- Map-based navigation using a global positioning system (GPS).
- Retro-traverse for communications loss. If the robot loses communications, it retraces its path until communications are restored.
- Indoor and outdoor two-dimensional mapping.

[*] iRobot 310 Small Unmanned Ground Vehicle is a registered trademark of iRobot Corp.
[†] Awarehead is a registered trademark of iRobot Corp.

Figure 1. iRobot 310 SUGV.

2.2.2 Operator Control Unit (OCU)

An Amrel Rocky DK8-M ruggedized tablet computer (figure 2) was used as the OCU to facilitate the four control conditions evaluated during the experiment.

Figure 2. Amrel Rocky DK8-M tablet computer.

2.2.3 Robotic Vehicle Controllers

2.2.3.1 Game Controller (GC/MC)

In this condition, the operator manually controlled all the robotic functions using a COTS Microsoft Xbox* 360 game controller (figure 3). The operator manipulated the game controller toggles and buttons to maneuver the robot and to manipulate the camera, flippers, and control arm.

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*Xbox is a trademark of Microsoft Corporation.

Figure 3. Game controller (GC/MC).

2.2.3.2 Virtual Joystick (VJ/MC)

When operating in the VJ/MC condition, all robotic functions were manually controlled through touch screen inputs. The operator used a stylus to manipulate the VJ, located in the lower left portion of the display (figure 4), to maneuver the robot. The touch screen stylus was also used to manipulate the camera, flippers, and control arm using the control menu shown in figure 5.

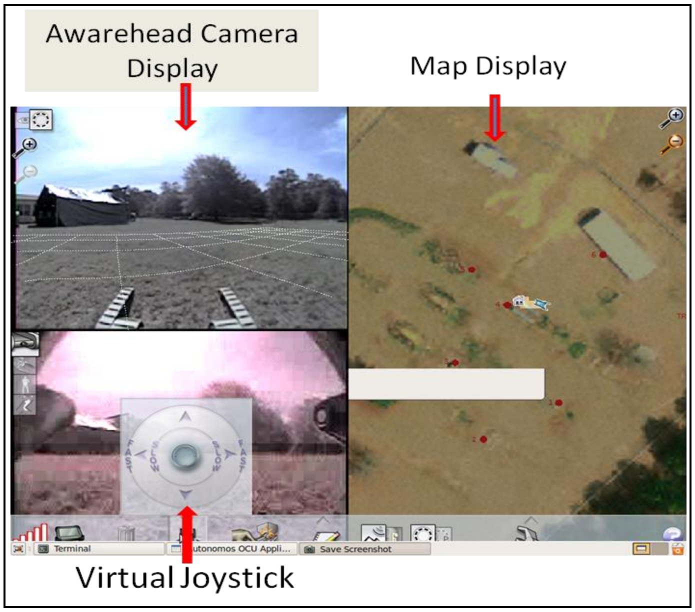

Figure 4. Virtual joystick (VJ/MC).

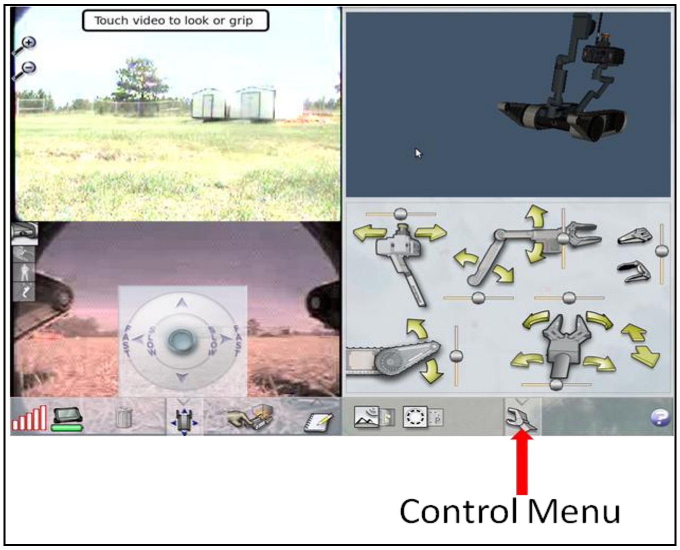

Figure 5. VJ/MC control menu.

2.2.3.3 Virtual Joystick with Click to Navigate (VJ/CN)

In addition to the MC options of the VJ, VJ/CN enabled the operator to establish waypoints on the map or select a location on the video display for the robot to maneuver to by touching the screen with the stylus (figure 6). Once the operator selected a waypoint or location on the video display, the robot autonomously maneuvered to the selected location.

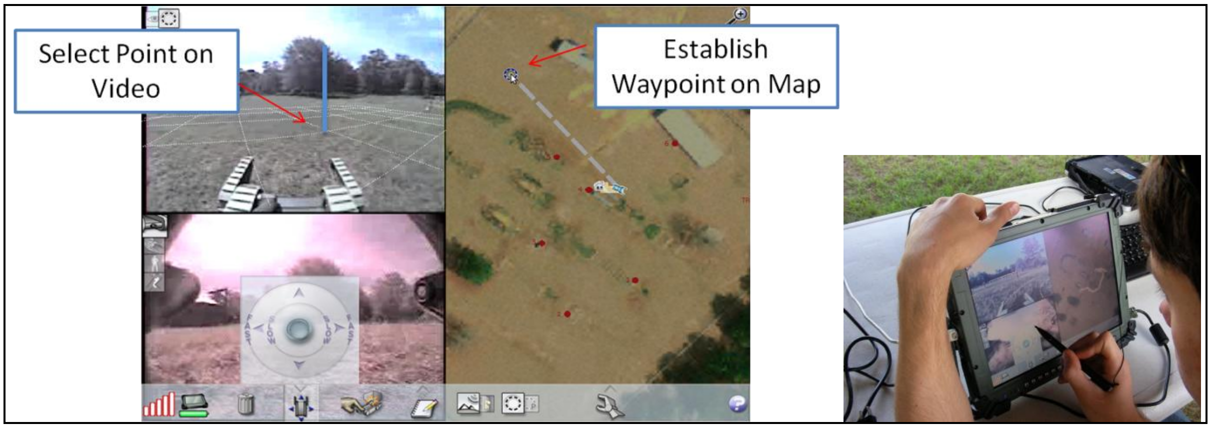

Figure 6. Virtual joystick with click to navigate (VJ/CN).

2.2.3.4 Game Controller with Click to Navigate (GC/CN)

In addition to the MC options of the GC, GC/CN enabled the operator to establish waypoints on the map or select a location on the video display for the robot to maneuver to by touching the screen with the stylus (figure 7). Once the operator selected a waypoint or location on the video display, the robot autonomously maneuvered to the selected location.

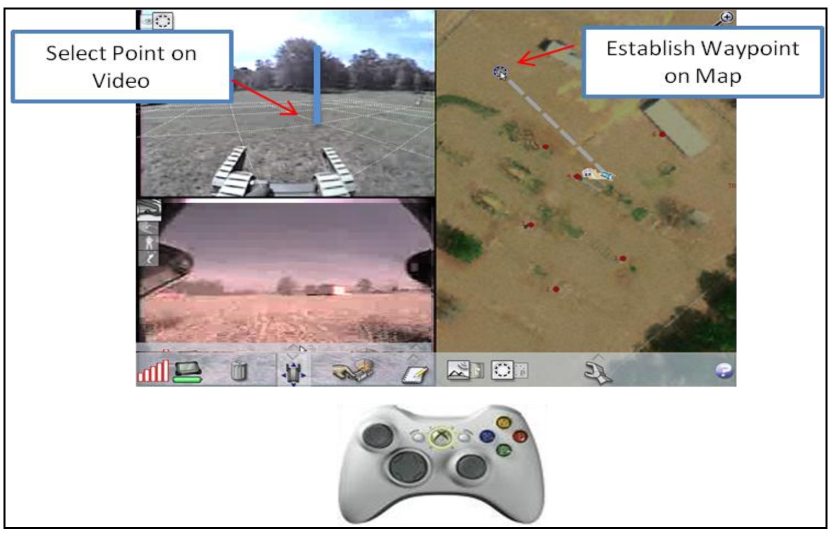

Figure 7. Game controller with click to navigate (GC/CN).

2.2.4 Robotic Reconnaissance Course

The robotic reconnaissance course (figure 8) was ~200 m in length, with five stations dispersed along a route. The stations included a bunker, tent, foxhole, tunnel, and a zigzag path. Each station had a simulated unexploded ordnance (UXO) located in or around them. Obstacles were placed around the entrance of the stations requiring the operator to maneuver the robot into position to locate the UXO. Participants were located out of the line of sight of the course in a stationary position inside a tent near the course.

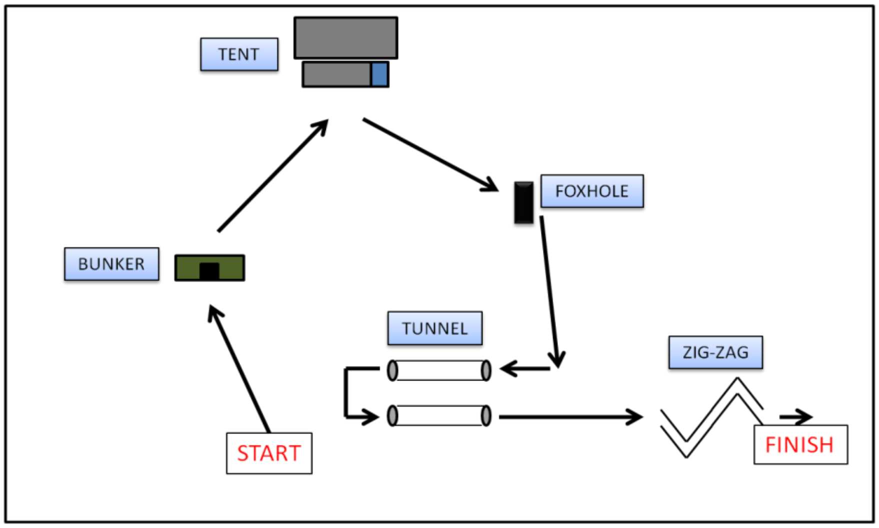

Figure 8. Robotic reconnaissance course.

2.2.5 The National Aeronautics and Space Administration-Task Load Index (NASA-TLX)

The NASA-TLX requires the user to rate the workload of a device on a number of different scales and to assign an importance weight to each scale. The scores on the workload scales (mental, physical, temporal, performance, effort, and frustration) can be combined in an overall workload score (Hart and Staveland, 2008).

2.2.6 Questionnaires

The questionnaires were designed to elicit Soldiers' opinions about their performance and experiences with each of the controller systems. The questionnaires asked the Soldiers to rate the devices on a seven-point semantic differential scale ranging from "extremely bad/difficult" to "extremely good/easy." Questionnaires were administered to each Soldier at the end of each iteration (with each control condition) and at the end of the experiment. Questionnaires were also used to gather information concerning the Soldiers' demographic data, robotic experience, and physical characteristics that might affect their ability to operate the robot.

2.3 Procedures

2.3.1 Soldier Orientation

The experiment Soldiers reported in groups of four for one day each, from 0800 to 1700 h daily. Upon arrival, they received a roster number used to identify them throughout the evaluation. The Soldiers completed an informed consent form, medical status form, and a demographics questionnaire. They were given an oral operations order that explained the robotic mission that they would undertake during the experiment. The training and robotic courses were also explained, and any questions the Soldiers had concerning the experiment were answered.

2.3.2 Training

A representative from iRobot trained the Soldiers on the operation of the iRobot 310 SUGV. Soldiers practiced teleoperating the robot on a training course with stations similar to those they would encounter on the reconnaissance course to mitigate learning effects. They were trained on each controller just before executing the course with that controller. Soldiers were considered trained once they were able to complete the training course without assistance. The average training time required was 20 min. A questionnaire concerning the amount of practice time given, the level of detail presented, and the adequacy of training aids was administered at the completion of training (appendix B).

2.3.3 Robotic Reconnaissance Course Iterations

During the operations order, Soldiers were told their mission was to conduct a reconnaissance of five checkpoints plotted on the OCU map and report any UXO found at each checkpoint. They were instructed to reconnoiter each checkpoint in order as quickly as possible without hitting any objects with the robot. As a secondary task, Soldiers were also told to report course time via radio when prompted.

Soldiers negotiated the course four times, once using each of the controller types. A data collector following the robot recorded the time to complete each station and the number of driving errors committed. The operator was given a "forward" driving error for causing the robot to hit an object when maneuvering the robot forward. If an object was hit when the robot was reversing, a "rear" driving error was recorded. The data collector with the robot also called the operator via radio two times per station and asked for the course time. A data collector co-located with the operator recorded the amount of time the Soldier took to respond to the secondary task and recorded whether the Soldier stopped the robot to respond or was able to respond while simultaneously operating the robot. Table 1 shows the order of treatments for each condition. There were two levels of controller (GC vs. VJ) and two levels of autonomy (MC vs. CN). After completing each iteration, the Soldiers were given a questionnaire designed to assess their performance and experiences with each of the control systems. The participants also completed the NASA-TLX after each iteration.

2.3.4 End of Experiment Questionnaire

After completing both courses, the Soldiers completed an end-of-experiment questionnaire that compared each of the controllers on a number of characteristics. They also completed questionnaires concerning the information requirements for teleoperating the robot.

Table 1. Order of treatments.

Roster	Iteration			
	1	2	3	4
1, 22	GC/MC	VJ/MC	VJ/CN	GC/CN
2, 23	GC/CN	GC/MC	VJ/MC	VJ/CN
3, 24	VJ/CN	GC/CN	GC/MC	VJ/MC
4, 21	VJ/MC	VJ/CN	GC/CN	GC/MC
5, 20	GC/CN	VJ/CN	VJ/MC	GC/MC
6, 17	GC/MC	GC/CN	VJ/CN	VJ/MC
7, 18	VJ/MC	GC/MC	GC/CN	VJ/CN
8, 19	VJ/CN	VJ/MC	GC/MC	GC/CN
9	GC/MC	VJ/CN	VJ/MC	GC/CN
10	GC/CN	GC/MC	VJ/CN	VJ/MC
11	VJ/MC	GC/CN	GC/MC	VJ/CN
12	VJ/CN	VJ/MC	GC/CN	GC/MC
13	GC/CN	VJ/MC	VJ/CN	GC/MC
14	GC/MC	GC/CN	VJ/MC	VJ/CN
15	VJ/CN	GC/MC	GC/CN	VJ/MC
16	VJ/MC	VJ/CN	GC/MC	GC/CN

3. Results

3.1 Demographics

The 24 participants were recruited from the OCS located at Fort Benning, GA. The average age of the Soldiers was 29 years, and the average time in service was 6 months. None of the Soldiers had any prior military experience in teleoperating a ground unmanned robot. Detailed responses to the demographics questionnaire are available in appendix A.

3.2 Training

Participants stated the training they received was thorough and fully prepared them to perform the tasks required to conduct the robotic reconnaissance course. Learning to operate the controls and drive the robot was rated as being easy for all controllers. Several Soldiers indicated that the hardest task to learn was maneuvering the robot in confined spaces with both the virtual and game control conditions. Several Soldiers commented that the simplicity of the Android made it easy to learn to use. Detailed responses to the training questionnaire are available in appendix B.

3.3 Robotic Reconnaissance Course Results

During pilot testing, it was discovered that the robot's maximum speed was less when the VJ was used than when the GC was used. The maximum speed with the GC was 0.940 m/s and with the virtual controller it was .455 m/s. The variations in speeds were set within the software and could not be changed prior to the experiment. Since there was no record of how much time in each condition was spent at maximum speed, course time data were not analyzed. Summary statistics for the rest of the performance data are shown in table 2.

Table 2. Means and (SDs), performance data.

Condition	Errors Forward	Errors Backward	UXO Detected
GC/MC	6.09 (5.39)	1.36 (1.84)	4.95 (0.21)
GC/CN	7.68 (4.90)	2.00 (2.74)	4.91 (0.29)
VJ/MC	5.50 (4.26)	1.27 (1.49)	4.68 (0.65)
VJ/CN	6.18 (4.95)	0.95 (1.25)	4.82 (0.40)

For driving errors forward, there was no significant main effect for controller ($F < 1$), no significant main effect for autonomy [$F(1,21) = 2.87$, $p = 0.105$, $\eta^2_p = 0.120$], and no significant controller x autonomy interaction($F < 1$). For driving errors backward, there was no significant main effect for controller [$F(1,21) = 2.48$, $p = 0.130$, $\eta^2_p = 0.106$], no significant main effect for autonomy ($F < 1$), and no significant controller x autonomy interaction [$F(1,21) = 2.75$, $p = 0.112$, $\eta^2_p = 0.116$].

In terms of number of UXOs detected, the main effect for controller approached statistical significance, $F(1,21) = 4.05$, $p = 0.057$, $\eta^2_p = 0.162$. The mean for the GC was 4.93 (Standard Deviation [SD] = 0.25), while the mean for the VJ conditions was 4.75 (SD = 0.53). The main effect for autonomy was not significant, ($F < 1$), nor was the controller x autonomy interaction [$F(1,21) = 1.65$, $p = 0.213$, $\eta^2_p = 0.073$].

Table 3 summarizes the secondary task data. For the response latency data, there was no significant main effect for controller, $F(1,19) = 1.70$, $p = 0.208$, $\eta^2_p = 0.082$. There was, however, a significant main effect for autonomy, $F(1,19) = 7.13$, $p = .015$, $\eta^2_p = 0.273$. Latencies were significantly shorter in the MC conditions (M = 2.9, SD = 0.7) than in the CN conditions (M = 3.4, SD = 1.0). The controller x autonomy interaction was not statistically significant, $F(1,19) = 1.01$, $p = 0.328$, $\eta^2_p = 0.050$.

Table 3. Mean and (SD), secondary task requests.

Controller	Latencies (s)	Stops
GC/MC	2.8 (0.8)	8.80 (2.17)
GC/CN	3.2 (0.8)	4.15 (3.03)
VJ/MC	2.9 (0.7)	5.75 (4.14)
VJ/CN	3.6 (1.1)	3.50 (2.93)

For the number of stops (figure 9) both the main effects for controller [$F(1,19) = 7.36$, $p = 0.014$, $\eta^2_p = 0.279$] and autonomy [$F(1,19) = 21.3$, $p < .001$, $\eta^2_p = 0.529$] were statistically significant. In addition, the controller x autonomy interaction was statistically significant, $F(1,19) = 4.75$, $p = 0.042$, $\eta^2_p = 0.200$. Post-hoc paired *t*-tests were conducted using the Bonferroni correction for multiple comparisons. With the CN feature, there was no significant difference in the number of stops between the GC and the VJ controllers, $t < 1$. With MC, there were significantly more stops with the Xbox controller, $t = 4.01$, $p < 0.05$.

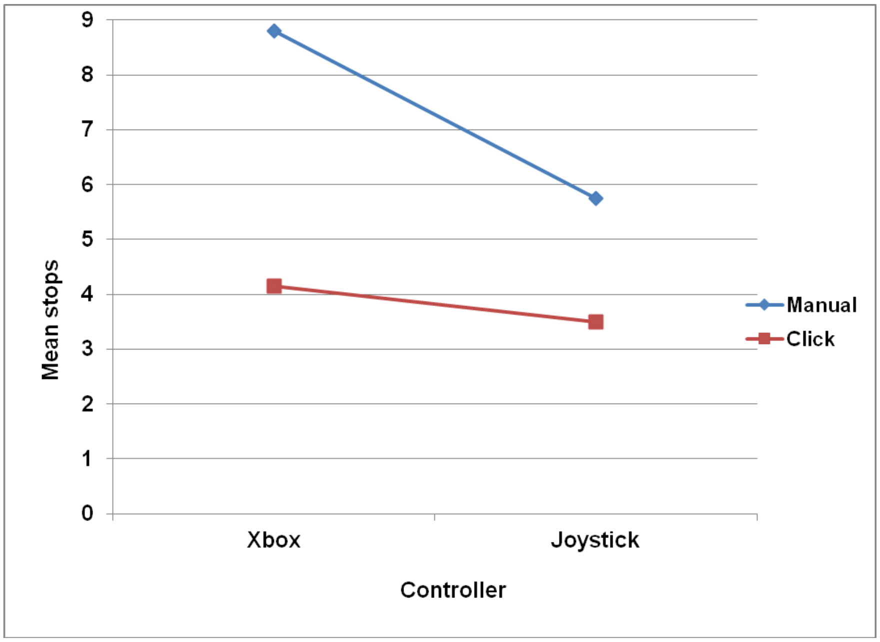

Figure 9. Mean stops, secondary task.

3.4 NASA-TLX Results

Table 4 shows the mean NASA TLX scale scores and total workload scores for the four controller conditions.

Table 4. Means and (SDs), NASA TLX.

Controller	Mental	Physical	Temporal	Performance
GC/MC	41.1 (28.4)	20.5 (20.5)	37.3 (24.9)	28.4 (23.8)
GC/CN	53.6 (24.3)	24.5 (19.7)	42.5 (20.4)	43.9 (24.1)
VJ/MC	50.9 (22.0)	31.4 (24.6)	43.0 (20.5)	36.8 (21.1)
VJ/CN	52.3 (25.5)	29.8 (24.3)	44.3 (21.1)	44.3 (18.8)
Controller	**Effort**	**Frustration**	**Total**	—
GC/MC	35.9 (22.6)	25.7 (16.1)	35.2 (20.3)	—
GC/CN	46.4 (24.9)	37.7 (25.2)	47.3 (19.5)	—
VJ/MC	48.4 (20.6)	43.2 (23.5)	47.4 (18.7)	—
VJ/CN	46.8 (22.1)	44.1 (23.1)	48.6 (17.4)	—

The total workload means are show in figure 10. A repeated measures analysis of variance (ANOVA) yielded a significant main effect for controller [$F(1,21) = 11.6$, $p = 0.003$, $\eta^2_p = 0.356$], as well as a significant main effect for autonomy [$F(1,21) = 4.54$, $p = 0.045$, $\eta^2_p = 0.178$]. In addition, the controller x autonomy interaction was statistically significant, $F(1,21) = 4.47$, $p = 0.047$, $\eta^2_p = 0.176$. With the CN feature, there was no significant difference in total workload means between the GC and the joystick controllers, $t < 1$. With MC, mean total workload was significantly higher with the joystick than with the GC, $t = 4.33$, $p < 0.05$. This same pattern of results is evident on the NASA TLX subscales means.

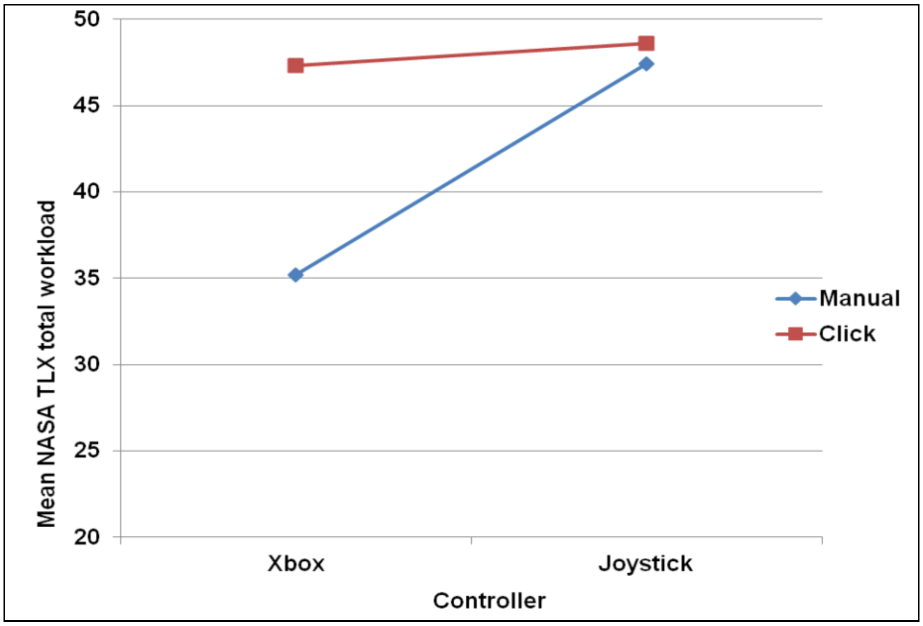

Figure 10. NASA TLX total workload means.

3.5 Questionnaire Results

Upon completion of each iteration of the robotic reconnaissance course, Soldiers were asked to rate their ability to perform the robotic maneuver tasks using each controller. The tasks were rated using a seven-point scale with one being extremely difficult and seven being extremely easy. Table 5 shows the maneuver tasks and ratings for each controller. The GC received the highest rating for every task except for the ability to multitask (drive and communicate on the radio). The ratings indicate that the participants preferred MC over CN for performing driving tasks.

Table 5. Mean maneuver task ratings.

Driving Tasks	GC/MC	GC/CN	VJ/MC	VJ/CN
a. Move the robot in the correct direction	5.95	5.23	5.05	4.50
b. Avoid obstacles	5.27	4.36	4.68	4.18
c. Turn quickly	5.82	4.64	4.05	4.18
d. Turn precisely	5.36	4.18	4.45	4.14
e. Anticipate whether turn radius of vehicle will allow a turn	5.14	4.23	4.41	4.14
f. Stop quickly	5.45	5.27	5.27	5.05
g. Get up to speed quickly	6.00	5.82	3.91	4.55
h. Adjust to effects of system latency (lag)	4.95	4.00	4.50	3.73
i. Adjust to the feel of the control system	5.77	5.23	4.95	4.36
j. Use the map to plan route in advance	5.55	5.18	4.50	5.00
k. Drive at slowest speeds	4.77	4.86	5.45	5.36
l. Drive at medium speeds	5.23	5.09	4.77	4.95
m. Drive at fastest speeds	5.86	5.41	4.05	4.45
n. Finish the course quickly	5.59	5.05	3.91	4.32
o. Responsiveness of the robot to your commands	5.64	4.86	4.68	4.5
p. Drive a straight route	5.55	5.14	5.00	4.68
q. Drive a route with multiple waypoints	5.41	4.77	4.82	4.68
r. Maintain situation awareness	5.59	5.32	4.82	4.59
s. Navigate to the next waypoint	5.59	4.73	4.91	4.82
t. Ability to multitask (drive &communicate on the radio)	4.68	4.45	5.00	4.32
u. Overall ability to perform this mission	5.77	4.91	4.68	4.77

Upon completion of all iterations, Soldiers were asked which of the four controller conditions they preferred for performing various maneuvering tasks. Table 6 shows the number of preferences for each controller for each maneuver task.

Table 6. Controller preference.

Driving Task	GC/MC	GC/CN	VJ/MC	VJ/CN
Avoiding obstacles	13	3	5	1
Accessing terrain for navigability	14	5	0	1
Driving a straight route	11	5	4	2
Driving a route with multiple waypoints	9	9	1	3
Performing the radio task while using the controller	6	2	11	2
Overall route reconnaissance	11	7	3	1

With the exception of performing radio tasks and driving a route with multiple waypoints, the ratings show an overall preference for using the GC to perform the reconnaissance course maneuver tasks. Several Soldiers stated their preference for the GC was due to their familiarity from playing computer games. Others felt that the robot was more immediately responsive to the GC's inputs and, thus, it was much easier to maneuver between closely spaced obstacles with it than with the virtual controller.

The GC also allowed the operator the ability to manipulate the camera and maneuver the robot simultaneously, whereas the two tasks were performed sequentially with the VJ. One Soldier stated: “Adjusting the flippers and then moving the camera with VJ control was time consuming. I could do both at the same time with the GC. I had to frequently switch between screens in order to use all of the robot’s functions.” Also, Soldiers were able to control the robot with the GC without looking at the controller. Soldiers had to visually pay attention to where the stylus was placed on the VJ relative to the direction they wanted the robot to move because it provided no haptic feedback.

Some Soldiers had more difficulty performing the secondary radio task while using the GC because for some tasks, both of their hands were required to manipulate the controller. They had to put down the controller in order to respond to the radio query forcing sequential performance of the primary and secondary tasks. Since the VJ only required one hand, they were able to accomplish both tasks simultaneously.

Even though overall ratings showed a preference for the GC, many Soldiers complained that it was too sensitive and caused them to over compensate when maneuvering around tight spaces. Soldiers stated they would like a function that would allow them to adjust the controller sensitivity similar to adjusting a mouse curser on a computer.

Several Soldiers stated that using the stylus was tedious and their hands and arms became fatigued during the VJ iterations. One Soldier also complained that his hand that held the stylus often obscured the video display. Several Soldiers stated that they would have preferred to have the display lay flat on the table when using the VJ but, due to overheating, the display was propped up at an angle to allow for heat dissipation. They had to visually pay attention to where the stylus was placed on the VJ relative to the direction they wanted the robot to move. Many of the Soldiers noticed that the virtual controller did not allow them to drive as fast as they could with the GC and complained that this adversely affected their driving speeds.

The participants generally preferred MC over CN, although some found the ability to autonomously maneuver the robot provided them more freedom to perform a secondary task. After completing the reconnaissance course with the VJ with CN, one Soldier stated: “This combination represents the most user friendly of the ones tested today. I could cover large areas quickly, multi-task, and make small adjustments to avoid obstacles.” Similar comments were made for both of the CN conditions. Several Soldiers also noted that the CN function would be most useful when large distances had to be traversed. Soldiers that had problems with the CN function often said that while it was great for long distances in open terrain, it was difficult to use for short distances and when sudden maneuvers were required because they were unable to see obstacles far enough in advance to avoid them. Others complained that when the robot was operating in the autonomous mode with the CN, imprecise or inaccurate GPS data took the robot off course, causing them to constantly re-click.

Soldiers experienced occasional video lag in all four conditions. The latency between control inputs and the robot's response sometimes caused driving errors. The lag was caused lapses in communication between the OCU and robot. Soldiers also occasionally experienced a shift in GPS locations in the CN conditions. The GPS shifts caused the robot to take unintended routes often resulting in errors. The GPS shifts were caused by poor satellite coverage.

Detailed responses to the post iteration and end of experiment questionnaires are available in appendices C and D.

4. Limitations

The results of this experiment were adversely affected by the inability to adjust the robot's maximum speed to be the same with the virtual controller and the GC. This added an uncontrolled variable to the course completion time data and the completion times should have been important performance measures. Also, radio communication between the OCU and robot was adversely affected when the robot was not in line of sight of the OCU antenna. Line of sight obstacles restricted where waypoints could be located and limited the distances between them. These limitations did not allow a full evaluation of the usefulness of the CN features on performance because the short distances did not free up long enough periods of operator time to show increases in secondary task performance.

5. Discussion and Recommendations

Although there was no significant difference in terms of driving errors between the controller conditions, Soldiers expressed an overall preference for the GC for manual control of the robot. The rubber thumb toggles are intuitive for driving the robot; this is especially true for the many Soldiers who frequently play video games using the GC (Pettitt, et al., 2011). The game industry has spent a lot of money on human-interface technology because it has such a huge market and this controller has benefited from significant human factors research. It is portable, durable and ergonomically designed. The thumb is a precise pointing instrument and requires very little energy as opposed to the stylus engaged virtual controller. However, the simultaneous tasks of driving the robot and camera arm manipulation could not be performed with the GC and its sensitivity could not be adjusted. Several Soldiers had difficulty operating the robot because the GC was so sensitive; they were unable to make the robot perform small, precise movements.

The virtual controller was less intuitive and the stylus required more effort to use than the thumb toggle on the GC. Use of the stylus was necessary because of the small size of the interface. Another more Soldier-friendly method of engaging the control is needed. A stylus can easily be lost, was uncomfortable to use, and Soldiers also had to continuously look at the virtual controller when driving the robot to ensure that the stylus was in the correct location. Haptic feedback from the virtual controller could alleviate the requirement to look at the control since the Soldier would be able to feel whether the control was engaged and which position of the control was engaged (i.e., north, south, east, or west).

The CN technology, which allows the operator to select desired waypoint locations, should, in theory, require less involvement from the operator than true teleoperation systems. However, effective CN systems rely on precise GPS positioning, which was intermittent during the experiment.

6. Conclusions

This experiment demonstrated that the concept of CN is a good in that it can enhance the operator's ability to multi-task. However, more work needs to be done for it to perform to the level that is needed for military operations. Also, if touch screens are used to save space on robotic controllers, they need to provide haptic feedback so the operator knows when a control is engaged without looking at it or the robot. They also need to be large enough for finger operation since a stylus is uncomfortable to use and could be easily lost unless it is tethered to the controller.

The GC needs to allow the operator to control the sensitivity of the controller to movements based upon the operator's needs. This would result in fewer driving errors in small areas or when the robot is close to obstacles.

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Appendix A. Training

This appendix appears in its original form, without editorial change.

TRAINING

SAMPLE SIZE = 22

1. Using the scale below, please rate the training that you received in the following areas:

1	2	3	4	5	6	7
Extremely bad	Very Bad	Bad	Neutral	Good	Very Good	Extremely Good

	MEAN
a. Introductory robotic training *(comments below)*	
Completeness of introductory training	6.27
Comprehension of the overall concept of the robot	6.36
b. Area reconnaissance training *(comments below)*	
(1) Robotic driving	
How to drive the robot (Game Controller)	6.23
How to drive the robot (Virtual Joystick)	5.59
How to drive the robot (Click to Navigate/Virtual Controller)	5.64
How to drive the robot (Click to Navigate/Game Controller)	5.77
(2) Time provided to practice driving robot on route reconnaissance course	
Game Controller	6.18
Virtual Joystick	6.09
Click to Navigate/Virtual Controller)	6.00
Click to Navigate/Game Controller)	6.09
(3) Explanation of how to complete the route reconnaissance course (independent of controller type)	6.35

<u>**Comments**</u>	<u>**No. of Responses**</u>
a. Introductory robotic training	
Easy to use.	1
Very easy to pick up the concepts of how to control the robot.	1
There was plenty of time for me to learn the controls, functions, and purpose of the robot.	1
Controls were simple and training explained how to use the robot very well.	1
Well over what was needed.	1
Took the time to answer my questions. Stopped me when I tried to go too fast to explain something. Was good.	1

b. Area reconnaissance training

Understood completely; easy to learn.	2
I was told exactly how to complete the route reconnaissance course.	1
The instructors were very informative on the course, the robot, and the controls.	1
I was given plenty of explanation of each feature and plenty of time to practice.	2
Adequate.	1
Ability to control is cumbersome (C2N/GC).	1
Lots of practice.	1

c. Building reconnaissance training

I was told exactly how to complete the building reconnaissance course.	1
I knew it was being timed, but I never felt like anyone was rushing me – very comfortable setting.	1
Adequate.	1
Sufficient to finish activity.	1
Not much practice with virtual control.	1

2. What were the easiest and hardest training tasks to learn?

Easiest

Fairly easy to learn how to use all of the interfaces we used today.	1
Easy to get a grasp on things once I gave it a try.	1
Picking up speed. With all controls except the virtual controller.	1
Game controller concept is intuitive and most people know how to operate it already.	1
Using the game controller.	9
Game controller because all the controls were condensed at one location.	1
Game controller with click to navigate.	1
Click to navigate.	1
Game controller is exactly same as game systems I have used.	2
Virtual controller/joystick.	1
I have used similar click to navigate systems as car navigation systems.	1
Camera manipulation.	1
Robot turning.	1
Robot direction, L, R, forward, back.	1
Driving forward and backwards, turning.	1
Steering; controls.	1

Hardest

The virtual controller is probably superior to the game controller, but it took me some time to adjust to the interface of the system.	1
Learning to navigate tight spaces with the very sensitive game controller.	1
Navigation control.	1
Turning in tight spaces between obstacles.	1

Comments	No. of Responses
Game controller in tight spaces.	1
Learning how to navigate the robot using the virtual controls in tight spaces.	1
Being able to judge how close I was to an object and if I had enough space around me to turn. Requiring precise movements from the virtual joystick was hard.	1
Click to navigate.	3
Click to navigate: it seemed that when I clicked, it would take strange routes. That, combined with occasional video lag, meant it was unpredictable and caused some driving errors.	1
Adjusting to input lag and the touch to navigate.	1
Virtual.	1
Virtual joystick menu.	1
Virtual joystick; less precise.	2
Virtual joystick was annoying.	1
Virtual controller was all new to me.	2
Figuring out virtual controls.	1
Putting the legs down when extending the camera forward.	1
Virtual control because the camera could be more intuitive.	1
Changing position of the camera to get a clear view of IEDs.	1
Controlling camera, head, up, down.	1
Adjusting the head, camera, etc., without joystick.	1
Remember which buttons did what on the game controller.	1
Multi-tasking with click to navigate and virtual controller.	1
Speed with virtual controller.	1
Getting used to the different methods of controlling the robot.	1
Situational awareness of obstacles out of view.	1
General Comments	
The navigate/virtual controller offers the best combination to the user to move quickly, accurately, and provide the ability to multi-task.	1
Virtual controls were the smoothest when training.	1
Game controller allowed ease of access to all features. Instead of having to switch to difference screens, if zoom was also available on remote would be great.	1
Game controller with click to navigate is the best option. I feel the game controller offers the best overall control and speed of the robot and the click to navigate adds a short cut for crossing long distances.	1
Combining the control types gives the operator full control of the robot.	1
Click to navigate made controlling the robot and its destination point difficult.	1
My generation was born with game controllers. We typically excel with video games and the familiarity lends itself well to using a game controller on a robot.	1

3. What are your overall comments on the training?

Comments	**No. of Responses**
Training was very good!	7
I normally don't give perfect scores on surveys, but everyone did a great job of prepping and explaining for this experiment.	1
Enjoyable training.	1
Simple, easy to learn.	3
Fun, intuitive, easy.	2
Very straightforward.	1
Instructors were patient and helpful, encouraging.	1
Very instructive as to the objectives that needed to be accomplished.	2
Training allowed me to manipulate the robot with relative ease and confidence.	1
I felt the training was thorough and my understanding of each controller was monitored and corrected during the testing allowing me to grow more comfortable.	1
The different interfaces were very easy to learn, much like teaching someone how to use consumer electronics. Soldiers of all skill levels should be able to learn how to operate the system in a short amount of time.	1
The staff more than adequately prepared me for the four iterations, and I felt if I had to go down range, I could use any of the systems if needed.	1
Impressive to see this technology in person.	1
Robots easy to control.	1
Training was complete and I was provided as much time as I needed to get used to the controls.	1
Need to work on the speed sensitivity of the robot with the different controls.	1
More time needed on virtual control practice.	1
I'm looking forward to the progress of IED defeat.	1

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Appendix B. Demographics

This appendix appears in its original form, without editorial change.

DEMOGRAPHICS

SAMPLE SIZE = 22

Sex	MOS	Rank	Duty Position
Male – 19 Female – 3	09S - 22	E-4 – 10 E-5 – 11 NR – 1	OCS – 22

Age	Height	Weight
29 years (mean)	70 inches (mean) (Range is 64 to 75 in)	171 pounds (mean) (Range is 130 to 210 lbs)

1. How long have you served in the military? 6 months
2. How long have you had an infantry-related job? 1 month
3. How long have you been a fire team leader? 0 months
4. How long have you been a squad leader? 0 months
5. How long have you been deployed overseas? 1.6 months

6 How long have you been deployed in a combat area? 1.6 months

7. With which hand do you most often write? 21 right 1 left
8. With which hand do you most often fire a weapon? 22 right 0 left
9. Do you wear prescription lenses? 11 No 11 Yes

9.a. If Yes, which do you most often wear? 8 Glasses 2 Contacts 1 Both

10. Do you wear glasses or contacts while firing a weapon? 11 Yes 11 No
11. Do you wear glasses or contacts while reading? 8 Yes 14 No
12. Which is your dominant eye? 19 Right 3 Left
13. What is the highest level of education you have achieved?

    0 GED 0 High School 0 Tech School 0 Some college
    19 College undergraduate degree 3 Master's degree

14. Where do you currently use a computer?

    18 Home 16 Work 4 Library 2 Other 0 Do not use

    Other: barracks room, everywhere

15. How often do you do/use the following?

	Number of Responses					
	Daily	**Weekly**	**Monthly**	**Once every few months**	**Rarely**	**Never**
Mouse	14	6	1	0	1	0
Joystick	0	2	1	3	10	6
Touch screen	14	2	3	2	1	0
Software with icons	19	3	0	0	0	0
Pull-down menu	17	4	0	0	1	0
Graphics/drawing features in software packages*	1	3	5	4	5	3
Email	16	4	2	0	0	0
Operate a radio-controlled vehicle	1	0	0	2	11	8
Play first shooter computer/video games	4	1	3	4	7	3

**One soldier had no response*

16. Using the scale below, please rate your skill level for each of the following activities?

1	2	3	4
None	**Beginner**	**Intermediate**	**Expert**

	Mean Response
Operating ground unmanned vehicles	1.38
Operating aerial unmanned vehicles	1.19
Target detection and identification	1.71
Playing commercial video games	2.62
Training with Army video simulations	2.00

17. How successful do you think you will be at robotic driving?

	Number of Responses
Very successful	3
Successful	11
Neutral	7
Unsuccessful	1
Very unsuccessful	0

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Appendix C. Post Iteration

This appendix appears in its original form, without editorial change.

POST ITERATION

SAMPLE SIZE = 22

A (GC/MC), B (VJ/MC), C (VJ/CN), D (GC/CN)

1. Using the scale below, please rate your ability to perform each of the following **tasks** based on your experience with the autonomy level that you just used:

1	2	3	4	5	6	7
Extremely difficult	Very difficult	Difficult	Neutral	Easy	Very easy	Extremely easy

DRIVING TASKS	**MEAN RESPONSE**			
	A	**B**	**C**	**D**
a. Move the robot in the correct direction	5.95	5.05	4.50	5.23
b. Avoid obstacles	5.27	4.68	4.18	4.36
c. Turn quickly	5.82	4.05	4.18	4.64
d. Turn precisely	5.36	4.45	4.14	4.18
e. Anticipate whether turn radius of vehicle will allow a turn	5.14	4.41	4.14	4.23
f. Stop quickly	5.45	5.27	5.05	5.27
g. Get up to speed quickly	6.00	3.91	4.55	5.82
h. Adjust to the effects of system latency (lag)	4.95	4.50	3.73	4.00
i. Adjust to the feel of the control system	5.77	4.95	4.36	5.23
j. Use the map to plan route in advance	5.55	4.50	5.00	5.18
k. Drive at slowest speeds	4.77	5.45	5.36	4.86
l. Drive at medium speeds	5.23	4.77	4.95	5.09
m. Drive at fastest speeds	5.86	4.05	4.45	5.41
n. Finish the course quickly	5.59	3.91	4.32	5.05
o. Responsiveness of the robot to your commands	5.64	4.68	4.50	4.86
p. Drive a straight route	5.55	5.00	4.68	5.14
q. Drive a route with multiple waypoints	5.41	4.82	4.68	4.77
r. Maintain situation awareness	5.59	4.82	4.59	5.32
s. Navigate to the next waypoint	5.59	4.91	4.82	4.73
t. Ability to multitask (drive and communicate on the radio)	4.68	5.00	4.32	4.45
u. Overall ability to perform this mission	5.77	4.68	4.77	4.91

2. Please comment on every task above that gave you difficulty and try to pinpoint the specific problem the system gave you.

Comments	**No. of Responses**
A	
I liked using just the controller. I felt in control of the robot at all times. The response was a lot better than the other method. Getting around barriers seemed a lot easier to maneuver.	1
Just put all controls on the controller.	1
This mode is nice for very close distances with obstacles.	1
All tasks were not difficult with the exception of maneuvering in tight spaces. I did not find this to be as fluid of a motion, more choppy and time consuming.	1
Compared to click to navigate, it does make multi-tasking a bit more cumbersome and to cover large open areas slower.	1
The overly responsive game controller was initially difficult, but I found that I adjusted fairly quickly to using it.	
The control is hypersensitive; overcompensated some times.	2
The game controller is a bit too sensitive and this shows most in tight confined spaces, such as the tunnels and the zigzag course. It makes multiple quick inputs necessary in order to correct and then overcorrect due to too much applied pressure. The function works very well as a throttle, but certainly affects precise turning.	1
Navigating through obstacles was a little difficult. It was easy to do this a low speed, but more difficult when you are trying to accomplish the mission quickly.	1
Whenever I responded to radio calls, I had to stop moving the robot, put down the controller, and pick up the radio, making multi-tasking difficult.	1
The most troublesome was stopping and picking up the radio. A headset would help a bunch. When going into the culvert, it was hard to see in. I could see myself running over something because of the lag or inability to see. Would probably be ok if I slowed down, but difficult.	1
The turn radius might be a little sensitive and turn too much.	1
It is tough to anticipate the turning radius.	2
The X-Y axis of the camera is counterintuitive.	1
Finding the ordinance clearly on the screen; poor video and camera quality.	1
The GPS was a little problematic; it didn’t point me in the exact direction.	1
Robot picks up speed too fast; controlling it was difficult.	2
I would like to be able to control the robot at a slower pace. In other words, I would want the robot to respond more sensitively to the controls when I want it to creep along once I’ve gotten close to the objective.	1
The only problem I experienced was when the system lagged. Because this interface is a lot more mobile and faster, when the system experienced lag, it was hard to maintain control of the robot.	2

Comments	**No. of Responses**
My issues were operator errors, not caused by the system.	1
Hitting the right turn happens too quickly.	1
It was difficult to communicate on the radio due to the fact that both of your hands are on the controller. Maybe a one-handed controller would be best.	1
I experienced a problem with the lag time between the robots camera/ antenna and the transmitting feed to the computer. It made it harder to control the robot's movements precisely. Every time the camera began to lag, I stopped moving the robot.	1
On the course with the wooden boarder and the robot is required to move up to the edge and peek over into a ditch, I had trouble with the depth perception of how close the robot's flippers and body were to the board. The robot turned over twice.	1
B	
I did like the menu system.	1
The time involved to go to put the flippers down and then move the camera with control; I could do both at the same time.	1
I would only use or want to use if I had many obstacles in my way and a short distance to cover.	1
Hand gets tired from the constant pressure needed on the screen. It was difficult to speed up the pace of the robot.	1
Lags.	1
Hardest to deal with the lag. It caused me to overcorrect when turning the robot, which made me almost run into a few obstacles.	1
Holding the 'pen' hand obstructs view of navigation. Pen was good at slow, precise movements, but was very tedious to hold up to the screen.	1
Navigating many of the obstacles seemed as if they would be nearly impossible at a medium or high speed.	1
Took time to get used to the controls. They weren't very precise sometimes; I would hit the left arrow and it would go too far left. Just difficult to be accurate with movement.	1
When moving it to right or left and point off to the side, etc., the robot appears to resist in readily responding to my wish for it to turn.	2
Interface is difficult. Small, precise maneuvers required slow movements, which seemed to slow the overall time.	1
Difficult to control.	1
Ability to control speed and turns without movement forward.	1
Sometimes the robot adjusted too much for level of input.	1
The system is very slow; the robot doesn't move fast.	2
The robot's responsiveness to changes in direction were slow.	1
The robot will not move faster than medium speed.	1
Hard to estimate the speed of robot.	1

Comments	No. of Responses
It was very slow to move between waypoints with this controller. The speed was very low the entire time.	1
Takes much longer to move from point A to B, which increases my frustration because I know this is a timed event.	1
Traveling from station to station with only the virtual console is time and effort wasted. A waypoint system is far more efficient so the operator does need to focus on keeping the stylus on the screen. Other than that, it is accurate, albeit laggy – slow, calculated turns are simple, but rolling, fluid ones require multiple corrections in confined spaces (tunnels, zigzag station).	1
Kept losing GPS.	1
Without using waypoint GPS, staying in waypoint order was achieved less.	1
Using just the virtual controller, I had to frequently switch between screens in order to use all of the robot's functions. In general, this slowed down the speed with which I completed the course. Slight decrease in situational awareness due to the need to activate a different menu to fully control the camera.	1
Maintaining situational awareness was difficult because you had to go through several steps to look around and could not multi-task two commands such as moving the boom arm and rotating the camera.	1
Ability to identify a camera focus spot.	1
Pointing the camera in the right direction can be hard when you have to move the arm where the main camera is located.	1
Difficult to adjust the lens/camera to see targets.	1
Difficult to move the camera, and time consuming.	1
Screen resolution can be a hindrance.	1
Not handy if my waypoint is far and I needed to multitask.	1
It was difficult to get the feel of this controller when trying to avoid obstacles. It was hard to turn precisely.	1
When it came to avoiding obstacles, turning quickly and precise movements, you have less control with the virtual joystick alone.	1
I prefer the hands-on controller instead; I feel I have more control.	1
C	
The virtual controller was far more accurate and vastly superior choice for any maneuvering around and amongst obstacles.	2
The waypoint function did work well and is the preferred method of movement between locations. Being able to drag the line and create multiple waypoints makes it far more controllable and easier to use over distance than babysitting the robot with the virtual controller.	1
The virtual joystick was very effective for making precise movements, but judging speed was more difficult.	1
I have to stop and change menu screens, which takes up time from the objective.	1

Comments	No. of Responses
When you swipe the stylus across the movement screen, the robot will begin to reset itself in order to move. This takes up precious time to complete each task.	1
When setting a directional path on the map section of the screen, the robot moves on the most direct path possible. The handbrake system in that event is an excellent idea, however, it's not quick enough in response to the robot's camera to catch foxholes or pitfalls that are along the way.	1
Moving in the correct direction with the click to navigate took several corrections to the plots pointed. However, the joystick was fairly straight forward.	1
The virtual controller was a little difficult to get used to and did not seem to be very precise when responding to my commands.	1
Adjusting camera/lens to view objects either below or above my line of sight gave me trouble.	1
Changing direction of the camera; not used to just pointing.	1
Camera could be more focused.	1
Too much sensitivity at times.	1
I really don't like using the touch to navigate. The robot was very jumpy and didn't respond how I wanted it to.	1
There was a point where I clicked the top left area to adjust the camera position and the robot moved forward.	1
I found that using this interface was precise, but movements are a lot slower than with the game controller.	1
Hard to control speeds.	1
Responsiveness to the click to navigate is slow.	1
The robot seemed to move too slowly with the virtual controller.	1
Very slow to get up to speed when going from one point on the map to another.	1
The speed and gauging the breaking.	1
Difficult to multi-task while using the click to navigate. I set a point for the robot, and then had to answer the radio, but the robot stayed on a straight path and hit an obstacle.	1
Robot moved to the waypoint too fast at times.	1
The straight ahead point would result in a zigzag motion.	1
Click to navigate would not proceed in straight line to waypoint.	1
The lines that show where the vehicle is going should reflect the turning radius of the robot.	1
Adjusting the neck on the robot. It's a conceptual challenge, easier to do with the joystick.	1
Switching from moving the camera and engaging the navigator.	1
Lag made it hard in tight spaces. GPS was off a little bit, but click to navigate made system easier to use, less frustrating.	1

Comments	**No. of Responses**
System lag when initiating click to navigate, because you don't see obstacles with enough advance warning so you can avoid them.	2
The GPS system? The lag caused a complete inability to navigate.	1
Click to navigate isn't precise enough to take me to my desired point.	3
Click to navigate (by itself) just isn't reliable enough for me.	1
It takes to too long to read instructions and proceed.	1
Waiting for the robot to set to drive mode.	1
If it was up to me, I would have driven the entire course with the virtual controller. Seemed the click to navigate put me in the wrong place and I would have to correct with the virtual controller anyway.	1
The click to navigate was often going to points where I didn't click.	2
Click to navigate would be fine if there were not so many obstacles.	1
Click to navigate moved randomly as it tried to orient toward the waypoint. This was a problem in tight quarters, with obstacles and caution tape nearby.	1
Clicking waypoints on the map itself was not very effective because of the robot's tendency to drive straight through caution tape.	1
Using the pen when right-handed caused me to put the pen down each time to speak on the radio because it wasn't a good idea to keep the robot in motion by point-click.	1
The virtual joystick took longer to adjust instruments and look around.	1
D	
Click to navigate is great for long distances, but difficult to control for short and sudden movements. Great for speed.	1
Using the game controller seemed more natural, even when traveling long distances over flat terrain. To compensate for the possibility of obstacles between the robot and the waypoint, I would click on waypoints located very close to the vehicle, resulting in short, and jerky movements.	1
I challenged myself to finish quickly, perhaps too quickly, and accordingly I had some driving errors in/around some of the obstacles. The problem was not system driven, just me not completely used to the system's functionality and wanting to execute quickly.	1
A lot of play in the controller.	1
Controller sensitivity. The robot responds very quickly and it's a little to responsive (not the robot's fault – totally a human problem).	1
The low quality of the video imagery made using click to navigate difficult because it was not always possible to see small obstacles between waypoints selected and the robot.	1
If there were some obstacles near the robot, it would stall the robot in carrying out click to navigate; take too long in deciding where to go or not to go anywhere.	1

Comments	No. of Responses
Hardest part of this controller was avoiding obstacles while moving between waypoints. Since the robot could not detect all obstacles, I had to be on the look-out when my robot was moving on the route I had set for it.	1
Would have to double click on screen to register destination location.	1
Click to navigate still had issues. I loved that you had more of the control on the controller. Maybe putting brake and camera zoom on the buttons.	1
Click to navigate is very difficult to use without constant input to adjust the seemingly random direction the robot takes using this system. It simply is not accurate, especially considering the robot moves at top speed while in this mode.	1
On click to navigate, the robot would spin around, not going directly to the point you wanted.	2
Click to navigate takes strange routes, causing you to use the emergency brake.	1
The click to navigate radius isn't far enough.	1
The head has to move to its natural position before click to move will move – this time is wasted considering the game controller allows movement regardless of the head's position.	1
Point 3 to point 4 did not navigate correctly on its own. Had to bring the robot back on course manually.	1
Moving the robot using the click to navigate was challenging because the robot would not proceed in a straight line to the point. The response time of the click to navigate screen was also a bit long.	2
It wants to "box" its way as it moves instead of traveling at an angle to the point on autopilot.	1
When I would touch the waypoint, the robot would take me out of bounds. I really didn't like using the point method. I had to stop the robot many times because it was about to hit a barrier. I felt like I didn't have very good control. Having the controller as a back-up helped out; allowed me to navigate better.	1
Felt I had less control when using the waypoints because the robot seemed to take unlinear routes and stopping the robot required reaching over and using the controller.	1
Hard to gauge where the robot will eventually end up.	1
Being able to respond to radio calls is difficult when one hand is holding the controller and another is holding the stylus. Either should suffice for a soldier to use; however, the option to have both available is beneficial.	1
Click to navigate sometimes lagged in carrying out the command; it would take a few seconds before moving.	1
Switching between controller to the pen is a hassle, especially when communication was necessary.	1

2. Please check any of the following conditions that you may have experienced during this trial.

CONDITION	Number of Responses			
	A	B	C	D
Motion sickness	0	0	0	0
Disorientation	0	0	0	0
Dizziness	1	1	1	1
Other (describe below)	3	2	2	3

Comments	**No. of Responses**
A	
Dizzy only because of time of day.	1
C	
Fingers get tired holding the stylus from constantly clicking the screen.	1
Everything is very fuzzy; can't tell what stuff is.	1

3. Using the scale below, what is your **overall rating** of the controller that you used this iteration?

1	2	3	4	5	6	7
Extremely bad	Very Bad	Bad	Neutral	Good	Very Good	Extremely Good

MEAN RESPONSE			
A	B	C	D
6.00	4.64	4.82	4.86

Comments	**No. of Responses**
A	
Excellent!	1
Very easy to use.	2
Easily adaptable to the X-box generation.	1
Two joysticks are good. The ability to operate the head and drive at the same time is good.	1
Felt more comfortable with a controller rather than a touch screen. Easier to use in my opinion.	1
Fast moving and accurate driving.	1
Felt natural and it was easy to control the vehicle.	1
The game controller is exceptional in nearly every aspect – intuitive, quick responding, accurate, and even ergonomic (compared to poking a screen with a stylus). With all the buttons mapped, no other form of control would be necessary (though waypoints are a nice feature).	2

Comments	No. of Responses
Great control and easy access to move mechanism on robot. No thought is needed to function/control.	1
I found it easier to be more precise when using the click to navigate/ controller combination to navigate the course.	1
This controller performed very well and responded well to my ‘commands.’ The only problem was that the robot could have been a little quicker to respond to my commands on the controller; however, this may be my perception only, and this may have been a result of ‘lag’ from the video camera.	1
I noticed that the zoom feature on the camera provides more clarity of picture to drive around than when the camera is set to its normal lens.	1
Handy when you’re close to target, but cumbersome over large distances.	1
Interface was a lot more streamline which allowed for a quicker completion of the course. It was a lot easier to handle and I felt like I exhibited more control over the robot.	1
The game controller is a bit too sensitive; picks up speed too fast.	1
Multitasking was difficult.	1
From dark to light, lighting was a little difficult to get over. Growing up on a ranch, experience with heavy equipment helped me become more self aware of what I was doing, especially time spent in a dozer.	1
Had minor difficulty turning the robot at minimal speeds precisely. My suggestion would be having the option to use both toggle switches to control each wheel track separately for more control over steering. Perhaps you could have the option to do that, and press the select button to switch back to have camera control.	1
B	
With only one hand necessary to hold the stylus and control the robot, it was easy to multi-task and answer the radio.	2
Because of the low speeds and ability to control the robot with one hand, multi-tasking with the radio was easy.	1
Virtual controller made it easy to maneuver around close obstacles.	
Good control of the robot with the virtual joystick.	1
Works well with minimal lag and provides accurate control in confined areas, as well as those with multiple obstacles; just so long as you take your time and finesse it over rushing.	1
Compared to the game controller, this one seemed slower for me to operate. The game controller feels more natural and I seemed to have a quicker reaction time with it instead of this one.	1
I felt as though top speed was slower.	1
The time involved to move the camera and not keep moving is frustrating; hard to multi-task controls.	1
Not as good as the game controller. It feels awkward holding the pen and placing pressure on the screen. A joystick is more intuitive.	1

Comments	No. of Responses
I had to keep my arm up to hold the pen on the screen the entire time, which made my arm tired.	1
Steering and turning were difficult. However, it moved the robot at much lower speeds so that helped to maneuver around obstacles. This also made it more difficult to move between waypoints because the robot would never move at a high speed.	1
I would have given this a better rating of 6 if the display lay flat (horizontally) on the desk. It would require less effort than working a vertical touch screen.	1
I didn't like using a stylus for operating the robot; I like the feel of a joystick better.	1
C	
Virtual controller with waypoint GPS system is vastly superior.	1
Controller allows for more precise turns and smaller movements. You have 100% control of the robot's turns and its head/flippers.	1
Using waypoints was a lot more efficient than using the controller and the pen. This system was very precise at navigating obstacles but seemed to be harder to control in the open.	1
Virtual joystick was easier to be smooth with. With practice would be easier. Plot points were fast, but I ran into some tape.	1
It was ok. A real joystick would be better.	1
This combination represents the most user friendly of the ones tests today. I could cover large areas quickly, multi-task, and make small adjustments to avoid obstacles.	1
The combination has a higher learning curve, and does not feel as natural as the game controller; but the joystick allows for precise movements and it was easier to multi-task on the radio.	1
I like the idea of the quick navigation using the point and click method, but the controller is slow to respond and it's actually easier to just maneuver it manually (with the virtual controller).	1
I felt comfortable using this controller at very low speeds to avoid the obstacles, but at medium to high speeds, I did not like the virtual joystick.	1
The touch to navigate adds speed.	1
The virtual control helps with accuracy and precision, but the other controls are difficult with the touch screen.	1
It was quicker to finish course by using click to navigate. Lag time was present but not enough to affect results. Easier than having to constantly steer robot forward.	1
Click to navigate is too worky, not accurate enough.	1
Not reliable or as accurate as the controller and virtual controller.	1
Need to improve camera clarity in order to identify objects better.	1
You feel a loss of control over the robot's actual directional movement forward and backward. It's less precise.	1

Comments	No. of Responses
After the game controller, the others seem a little more challenging to operate.	1
D	
The combination of click to navigation and game controller is best in my opinion. Easy to navigate with ability to move automatically without soldier need to constantly supervise. Allows for multi-tasking without losing time.	1
The combination is a good one. I could see how, if given enough time to practice, I could get quite good at maneuvering the robot quickly and efficiently.	1
The game controller for the most part is excellent, with few shortcomings.	1
The game controller was very effective for precise movements close to the objectives.	1
Game controller is a good backup.	1
Joystick made it easier to maneuver, better handling, and control for accuracy.	1
Use of the click to navigate was great for getting me on a straight course.	1
Easier to find my route to the waypoint because I didn't have to manually position the robot in the direction of the waypoint. Once I set the point, the robot oriented itself to the point.	1
Using only the controller was a lot easier than switching between the controller and the pen.	1
The click and move is very beneficial when it was time to multi-task, such as with the radio.	1
If the point and click was immediate, it would be the best overall system for the plethora of demands on the operator. If I can fully concentrate, I like to control it myself and of course I am faster. If the lag time was gone when I hit a waypoint it would be awesome. If it could travel not so boxy when it was on autopilot, it would even be better. It makes me nervous when it makes big "swings" back and forth when I am trying to talk on the radio.	1
The lag along with the frustration of the strange routes that click to navigate takes makes the click to navigate difficult.	1
Click to navigate seems more appropriate for longer distances.	1
This controller was more ideal for the longer distances between waypoints, as it gave me time to complete other tasks. However, when there were obstacles between waypoints, it was more difficult to avoid them with this controller.	1
Based on the grid and where the robot eventually stopped, it was hard to determine which square or point on the screen it was best to select.	1
It seems easier to just manually control the robot. The good thing was the GPS would get you going the correct direction most of the time, and then it was better to control it manually to the point.	1

Comments	No. of Responses
The click to move is not ideal, requiring too much input and effort compared to other methods of control.	1
Using the touch screen waypoint system seemed redundant.	1
Not reliable; too many errors (hitting barriers, running out of bounds). Wasn’t easy to control.	1

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Appendix D. End of Experiment

This appendix appears in its original form, without editorial change.

END OF EXPERIMENT

SAMPLE SIZE = 22

1. Please indicate your 1st, 2nd, 3rd and 4th choice of the level of autonomy to use for completing the following tasks. 1st choice = 3 points, 2nd choice = 2 points, 3rd choice = 1 point, and 4th choice = 0 points.

	GC/MC	VJ/MC	VJ/CN	GC/CN
Avoiding obstacles	52	38	13	29
Driving a straight route	45	26	23	37
Driving a route with multiple waypoints	42	20	27	43
Performing the radio task while using the controller	30	47	30	25
Overall route reconnaissance	49	25	17	41

Comments	No. of Responses
Talking on the radio and operating was the easiest with virtual controller.	1
The best control and easiest to pick up is the game controller.	1
The hardest part with each controller was avoiding obstacles in tight areas.	1
Avoiding obstacles whenever it was in an autonomous mode.	1
The game controller with the ability to set waypoints is the ideal set up, but adding in the virtual joystick for precise turning would be acceptable in lieu of adjusting the sensitivity of the game controller.	1
I couldn't trust the click to navigate to traverse a route for waypoint in a straight line.	1

2. What suggestions do you have for ways to increase the effectiveness of the:

a. Game Controller?

Comments	No. of Responses
Game Controller	
None, this is the best.	1
Better control of speed.	1
Allow a great variation of speeds. I wanted to be able to move slower to navigate obstacles.	1
Be able to control each wheel track independently with the toggle switches.	1
Faster responsiveness of robot to commands.	1
Maybe switch to a one hundred controller. Keep joystick.	1
Take a little of the play out.	1

Comments	No. of Responses
Ability to plot points, perhaps with something mounted on game controller.	1
Hands-free communication.	1
If game controller was only option, I would want a hands-free headset so I could communicate with my soldiers.	1
Put all functions on game controller.	1
Change the flipper controls so the top button is up and the bottom button is down (that's how I accidentally flipped the robot).	1
Change the button sequence to control the robot's neck. R1 the neck could move up, and R2, the neck moves down.	1
Decrease responsiveness (sensitivity).	9
Make joysticks less sensitive. I found it difficult to navigate in tight spaces.	1
More choppy motion than fluid.	1
Use "+" button, not just joystick.	1
A button on the game controller mapped for resuming driving mode would be useful.	1
Virtual Joystick	
Have a virtual dot.	1
Somehow give the user the ability to move much faster if needed.	7
Increasing the ease of turning while moving at speed. The response time seemed quite a bit slow.	1
Quicker response time.	1
More responsive to user's commands. I had trouble getting the robot to turn the way I wanted it to.	1
Mount screen horizontal instead of vertical.	1
I experienced system lag with this one so it's hard to say. I think I'd like to try a horizontal interface as opposed to the vertical computer screen.	1
Allow direction manipulation on the screen while navigation is engaged.	1
Add an auto forward option – holding the stylus up for long distance is tedious.	1
Add an additional camera to monitor the robot when it's backing up. So when the joystick is moved south, the camera view changes to reflect what's going on from behind.	1
Not as responsive as GC.	1
Not being able to multi-task movements.	1
The menu for controlling the movement of features on robot should be one picture of the robot with buttons to manipulate each part, not individual pictures of each feature. To me, it would be faster and easier to use.	1
Didn't like this one at all; too tedious to use.	1
Click to Navigate/Virtual Controller	
They both work together great.	1
Best option.	2
Slows during click to navigate. Difficult to avoid obstacles when the robot is moving fast on its own.	1
C2N: quicker response time when clicking destination, more precise	1

Comments	No. of Responses
navigation around obstacles.	
Fix the C2N – it zigzags straight lines and requires constant babysitting to guarantee its going where you want.	1
The C2N allows speed.	1
Make the C2N not so jumpy; more accurate.	1
Smoothing out the C2N, I ran into the tape a couple of times, which then required me to direct attention to over watch so it didn't get into trouble.	1
The C2N was redundant and unnecessary.	1
VC: quicker response time when clicking destination, more precise navigation around obstacles.	1
VC allows handling, but limits the ease of adjusting the robot, camera, flippers, etc.	1
Allow user to adjust the speed of the robot to avoid obstacles better.	1
More precise speed and turning controls.	1
I experienced system lag, as well but I think the combination works well (especially in tricky situations like multiple obstacles and tight spaces).	1
To increase performance, the controls would have to respond more readily with less lag time and more accuracy.	1
Difficult to navigate in tight terrain.	1
Mount screen horizontal.	1
Make robot's movement more predictable.	2
Better system of determining where the robot will end up.	1
With navigation system, it would be helpful to be able to detect obstacles in between large open areas.	1
The robot seems to point in the wrong direction when using click to navigate.	1
C2N robot needs to respond to your command in a straight line.	1
A better way to switch between camera mode and navigate mode.	1
Not being able to multi-task movements.	1
Navigate was not reliable.	1
Click to Navigate/Game Controller	
Game controller is the best.	1
Good combination, but hard to maneuver due to sensitivity of control.	1
Waypoints are a useful addition to the game controller.	1
Is great as is unless you change the type of controller to make the multi-tasking part less cumbersome. For instance, use the street fighter arcade controller layout (a joystick with six buttons).	1
They both work together well, but it's tough since they're separate machines. Hands are fumbling, plus the radio is more trouble.	1
Somehow find an easier transition between the pen for the click to navigate and the joystick.	1
Slows during click to navigate. Difficult to avoid obstacles when the robot is moving fast on its own.	1

Comments	No. of Responses
C2N: quicker response time when clicking destination, more precise navigation around obstacles.	1
C2N was a pain with the game controller because I had to constantly switch between the controller and pen.	1
One hundred controller so other hand can be free for radio comms.	1
More predictable robot movement during click to navigate.	1
Better system of determining where the robot will end up.	1
With navigation system, it would be helpful to be able to detect obstacles in between large open areas.	1
Mount screen horizontal.	1
I did not like this combination at all. The bulky controller was difficult to handle when switching back and forth from the click to navigate screen. A smaller, easier to handle controller could help with that.	1
Liked ability to stop navigation by simply directing robot back on joystick, easy to stop.	1
Allow direction manipulation on the game controller while navigation is engaged.	1
General Comments	
Both of the click to navigate options would be more effective with higher quality imagery so the operator has a better idea of what he is moving the vehicle toward.	1

3. Using the scale below, what is your **rating** of the human factors characteristics of system that you used curing this experiment?

1	2	3	4	5	6	7
Extremely bad	Very Bad	Bad	Neutral	Good	Very Good	Extremely Good

CHARACTERISTICS	MEAN
a. Display size for driving	5.14
b. Display size for seeing IEDs	4.91
c. Size of the buttons on the screen	5.27
d. Placement of the buttons and controls on the screen	5.09
e. Sensitivity of the touch screen	4.91
f. Latency/lag in the system	4.27
g. Ease of using the arm controller while using the game controller	5.95
h. Ease of using the arm controller while using the virtual controller	4.26
i. Ease of using the flippers while using the game controller	6.09
j. Ease of using the flippers while using the virtual controller	4.41
k. Usefulness of the video touch	5.36
l. Display layout	5.18
m. Map fidelity	4.64
n. Overall controller size for use in the field	5.73
o. Controller configuration for use in the field	5.73

Comments	No. of Responses
Mostly everything works great.	2
The best of all worlds was the game controller.	1
Display size was nice.	1
Regardless of system used, the more practice given the better the performance.	1
Perhaps using the GC for area recon and switching to virtual for closer/tight space objectives.	1
Controls for the robot using the virtual controller were difficult to access quickly.	1
Video resolution is poor.	1
Putting the screen down more like a tablet may be more comfortable.	1
Overall system is very sensitive.	1
Would opt for click to navigate/game controller. Would add additional features to remote. Minimize usage of screen for additional features currently not available on remote.	1
Imagery quality from the cameras mounted on the robot could be better.	1
On the screen, increase the size of the buttons.	1
On the game controller, a quick tap to move the robot on its current heading to free up a hand for another task.	1

Comments	No. of Responses
The map seemed to be slightly off from reality.	1
While using joystick, you had to stop all other tasks in order to manipulate flippers or arm/camera. The GC allowed for better multi-tasking.	1

4. What needs to be added to the controller to give you more knowledge of the area around the robot?

Provided for the most situational awareness thanks to the ease of use of the camera.	1
I was able to do everything I needed to during the mission.	1
Add zoom options to the controller.	3
Need a way to zoom in and out with just the game controller.	1
Something that could detect obstacles further out would be helpful.	1
Optional 360 view (wide angle front, rear, and sides of at same time) for maneuvering around obstacles.	2
More multiple cameras/video displays open simultaneously.	1
Cameras pointing behind to the sides of the robot.	2
For quickness, more cameras on the side that you can quickly toggle to. Hardly used chassis camera but when I did, it was helpful to orient main camera.	1
Better cameras with clearer definition.	1
A button that could allow fast access to a rear camera.	1
A button on the controller that allows for a quick change in camera angles.	1
A toggle button to quick view the side cameras. Rather than having to rotate robot head to look to sides. This would allow it to be more time efficient and would allow for quick security checks.	1
I had difficulty moving the video arm of the robot, especially with the virtual controller.	1
The driving display could have been better if it were larger.	1
Height sensors/info.	1
Manual focus, sensors.	1
A button on the controller that quickly resets the robot to roving mode.	1

5. Where would you like to see a robotic controller placed?

Number of Responses			
Wrist	Chest	Cargo Pocket	Other
5	4	12	4

Maybe a high tech visor.	1
Thigh area front.	1

Comments	No. of Responses
Anything that can be accessed relatively easily and does not add too much weight.	1
Bring in the system when needed; carry the controller in your rucksack.	1
If you were running and moving, it would be nice to have it strapped to you so you would not lose it when %$# hits the fan. Put it on a strap that will zip it back up when finished, so you can just drop it and grab your weapon if need be. The controller zips up to a secure spot on your chest, and you can grab it when you next have a change to continue mission.	1

6. Overall comments:

Hooah!	1
Great experience!	3
This was an extremely neat experience and I'm extremely fortunate and appreciative to have helped. I enjoyed it. Thank you!	1
Controller is my number 1! Virtual controller is number 2, and touch to navigate is number 3. The controller is easier to use and to get used to quicker.	1
System is good overall, comfortable and easy to master.	1
Much easier to control these robots than I had anticipated. Just like playing a video game.	1
The robot was very easy to use on the GC. My suggestions would be to allow customization of the controller layout to allow personalization to an individual soldier; and also be able to control each wheel track independently through both toggles, but be able to switch to camera and arm control. The menu for controlling features on the joystick could be condensed into a single picture with options for each different part. This could speed identification and selection of desired movements. Personally, I would use the C2N in wide open spaces across long distances, but no other time because I could not trust the system to proceed to the waypoint in a straight line. The zoom feature was great in the reconnaissance of routes and buildings, but the definition and clarity of the normal camera zoom was a little rough; could be sharper.	1
Overall, the click to navigate with game controller is my best option.	1
The game controller was the best.	2
Game controller has the most control.	1
Game controller was easiest to pick up.	1
I found the game controller to be the most streamline control system. However, the sensitivity of the controller's joysticks made navigating obstacles harder. Overall, I preferred the game controller.	1
The easiest to multi-task was the virtual land plotting waypoints.	1
Did not care for the click to navigate. It seemed to cause more issues. It was faster to just drive the robot.	1

Comments	No. of Responses
Maybe switch to a one hundred version if the user needs to have a hand free. Add zoom controls to the game controller. That was the only time I had to take my hands off the controller during iteration 3.	1
Using the game controller or virtual controller in combination with click to navigate seemed more trouble than it was worth, especially at the close ranges we were dealing with on the course. The combination options would be more useful in situations where the robot has a long distance to travel.	1
A combination of the game controller/virtual with plotting points would be the best configuration to tackle most missions. A few kinks worked out of the plotting waypoints so it's smoother in the auto pilot would be my only suggested improvement for the plotting.	1
Put a "continue on" trajectory button on game controller to facilitate multi-tasking.	1
If I was down range, I would want to use the click to navigate/virtual controller system.	1

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List of Symbols, Abbreviations, and Acronyms

ANOVA	analysis of variance
CN	navigate control
COTS	commercial-off-the-shelf
GC	game controller
GPS	global positioning system
HMI	Human Machine Interface
MC	manual control
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
OCS	Officer Candidate School
OCU	operator control unit
SD	standard deviation
SOURCE	Safe Operations of Unmanned Systems for Reconnaissance in Complex Environments
SUGV	Small Unmanned Ground Vehicle
UXO	unexploded ordnance
VJ	virtual joystick

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